DIGITAL MEASUREMENT OF ULTRASONIC VELOCITY

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INTRODUCTION

The ultrasonic material evaluation has been applied to composite materials and nonhomogeneous materials. In quantitative evaluation of these materials the ultrasonic velocity and attenuation are widely used. In addition acoustoelastic stress measurement requires high precision measurement of the ultrasonic velocity.

The sing-around and pulse-overlap methods, which are analog methods, have been used for the precise measurement of the velocity or time-of-flight [1]. In analog method when we want to measure the attenuation as well as the velocity, we need another measurement unit for the attenuation measurement. The appearance of high-speed digital wave memories with large data storage allows us to evaluate both the velocity and the attenuation simultaneously using the echo wave trains stored in the wave memory. The digital measurement system and the digital signal processing to ultrasonic pulse-echoes have been reported [2-4]. These results show the validity of the digital technique, however, these digital methods are not widely used.

The purpose of the present paper is to establish a simple but precise digital measurement system of the time-of-flight of ultrasonic pulse-echo. The measurement system is composed of a conventional ultrasonic pulser/receiver, a transducer, a high-speed digital wave memory and a personal computer. The time-of-flight is calculated with the zero-crossing, cross-correlation and phase spectral methods for the digitized echo wave trains. The validity of this digital method is demonstrated.

MEASUREMENT SYSTEM

The schematic diagram of the measurement system is shown in Fig.1. This is composed of ultrasonic pulser/receiver (Panametrics 5052PR), a transducer, A/D converter board (Sonix STR8100) and personal computer (IBM PC/AT compatible). This A/D converter board has minimum sampling interval of 1.25ns and 8bit resolution.

To improve the S/N ratio, the ultrasonic transmission/reception and the signal acquisition are repeated and the digitized signals are added in the computer. To improve the precision of the measurement, it is required that the jittering of the digitized signals does not occur. This A/D converter board transmits the trigger signal that is used for the

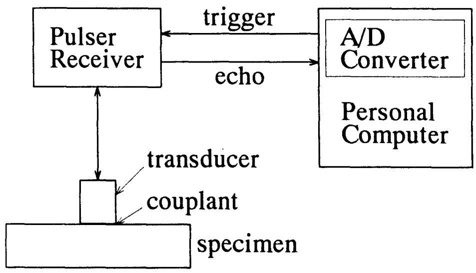


Figure 1. Digital measurement system

pulsed excitation of a transducer. This trigger signal synchronizes the sampling clock supplied to the A/D converter, therefore, the jittering does not occur.

CALCULATION OF TIME-OF-FLIGHT

Zero-Crossing Method

The time-of-flight is evaluated as the time difference of the zero-crossing point of two echoes as shown in Fig.2. For digitized waveforms, several data points around the zero-crossing point are fitted by a linear function. Then, the zero-crossing point is calculated as the intersection of the linear function and the horizontal zero line.

Cross-Correlation Method

The cross-correlation function is defined as

$$R_{xy}(\tau) = \int_{-\infty}^{\infty} x(t)y(t+\tau)dt \tag{1}$$

where $x(t)$ is a certain echo and $y(t)$ is another echo. τ is the time lag. If a medium is not dispersive and the attenuation does not depend on frequency, the echo $y(t)$ is expressed as

$$y(t) = \alpha x(t-T) \tag{2}$$

where α denotes the ratio of amplitude of two echoes and T is the time delay relative to $x(t)$, that is, the time-of-flight. Thus the τ that maximizes R_{xy} is equal to the value of T.

For digitized waveforms, the discrete cross-correlation function is defined as

$$R_{xy}(k) = \frac{1}{N}\sum_{n=0}^{N-k-1} x(n)y(n+k) \qquad (-(N-1) \le k \le N-1) \tag{3}$$

Two echoes $x(n)$, $y(n)$ are cut out as shown in Fig.3. The value of k that maximizes R_{xy}

in Eq.(3), k_m, may not be the real maximum of R_{xy} in Eq.(1) because the value of k is a discrete integer corresponding to the sampling interval. To evaluate the k^* that gives the real maximum of R_{xy}, three points around the k_m are interpolated by a quadratic function and the extremum of the quadratic function is regarded as the maximum of R_{xy}.

Phase Spectral Method

The above methods are applicable only for nondispersive media. If a medium is dispersive, the phase and group velocities depend on frequency. The phase and group velocities are determined with the phase spectra of two echoes. The phase spectrum is

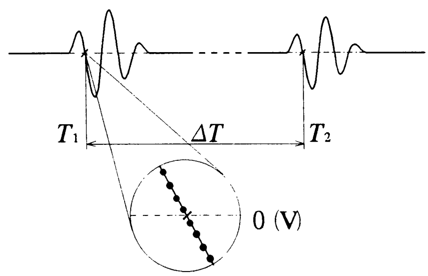


Figure 2. Zero-crossing method

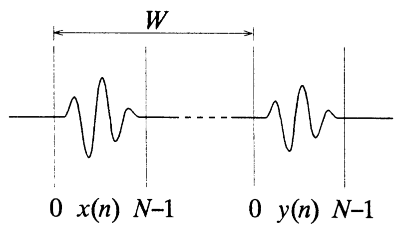


Figure 3. Cutting out echoes

obtained by discrete Fourier transform. The time-of-flight corresponding to the phase and group velocities are calculated by Ref.[4] as

$$T_p(n) = -\frac{\Delta\phi(n)}{\omega(n)} + W \tag{4}$$

$$T_g(n) = -\frac{\Delta\phi(n+1) - \Delta\phi(n-1)}{2\Delta\omega} + W \tag{5}$$

where $\Delta\phi(n)$ is the phase difference of two echoes and W is the time difference between two windows shown in Fig.3.

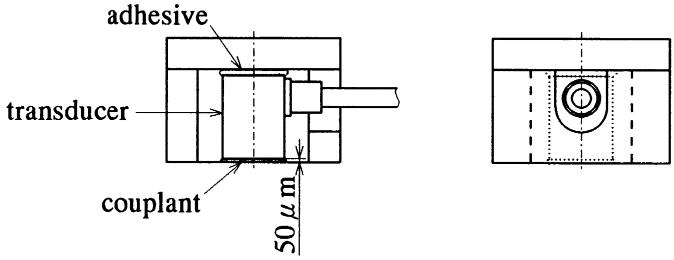


Figure 4. Control of couplant thickness for transverse wave

EXPERIMENTAL PROCEDURE

The measurement method just described was applied to the measurement of the longitudinal or transverse wave velocities of 2017–T3 aluminum alloy and SNCM439 steel alloy. For longitudinal wave, normal incidence transducer (Ultran, LC25–10, 10MHz, 0.25in.), low viscous glycerine couplant and an acrylic delay of 5mm thick were used. For transverse wave, normal incidence transducer (Panametrics, V156, 5MHz, 0.25in.) and high viscous couplant (Panametrics SWC) were used, whose thickness was controlled about 50μm with the fixture shown in Fig.4. The transducer was pressed on a specimen with the force of about 20N. The specimen and the transducer were covered with polyethylene film. This assembly was immersed in a water bath, of which temperature was controlled within ±0.02°C. The measurement was started after keeping the assembly in water for 10 minutes.

The ultrasonic pulse–echo trains were digitized with the sampling rate of 800MHz and added 256 times. Three signal processing procedure were applied to echoes B1 and B2. In the zero–crossing method, the first zero–crossing point was used. In the phase spectral method, fast Fourier transform was executed for 8192 data points with padded zeros.

RESULTS

Time–of–Flight of Longitudinal Wave

Figure 5 shows the time–of–flight of longitudinal wave measured for aluminum alloy plate of 10.052mm in thickness. To confirm the precision of the measurement, 10 times measurements were repeated without reattaching the transducer. The time–of–flight was calculated with the zero–crossing, cross–correlation and phase spectral methods. It should be noted that even though the same waveforms were used for three methods, the time–of–flight is different from one method to another.

The precision of the measurement, double of the standard deviation, is 4ps with the cross–correlation method, which corresponds to the relative velocity variation of about 1×10^{-6}. The phase spectral method for the phase velocity gives almost the same precision. The precision of the zero–crossing method is slightly lower.

Time–of–Flight of Transverse Wave

Figure 6 shows the time–of–flight of transverse wave of aluminum alloy. The phase spectral method was not used because the echo waveforms were disturbed by insufficient damping in the transducer used. The legend in Fig.6 denotes the time from pressing the transducer on the specimen to starting the measurement. The control of couplant thickness allows us to stable measurement for long time, if temperature would be kept constant.

The precision of the measurement, double of the standard deviation, is 8ps with the cross-correlation method. The relative precision is about 1×10^{-6}. The zero-crossing method gives lower precision.

Temperature Dependence of Longitudinal Velocity

The change in longitudinal velocity with temperature is shown in Figs.7(a) and 7(b) for aluminum and steel alloy, respectively. The temperature coefficient of the velocity is -1.6×10^{-4}/°C and -9.8×10^{-5}/°C, for aluminum and steel alloy, respectively. These values are consistent with those reported so far [5].

Influence of Specimen Thickness

Figures 8(a) and 8(b) show the velocity change with specimen thickness for aluminum and steel alloy, respectively. Apparently the higher velocity was obtained with decrease of specimen thickness. This tendency has been reported by McSkimin [6]. In this velocity or time-of-flight measurement, the diameter of transducer is the same order or less than the specimen thickness, therefore, the sound field may not be planar, as assumed in the simple theory of wave propagation of unlimited body.

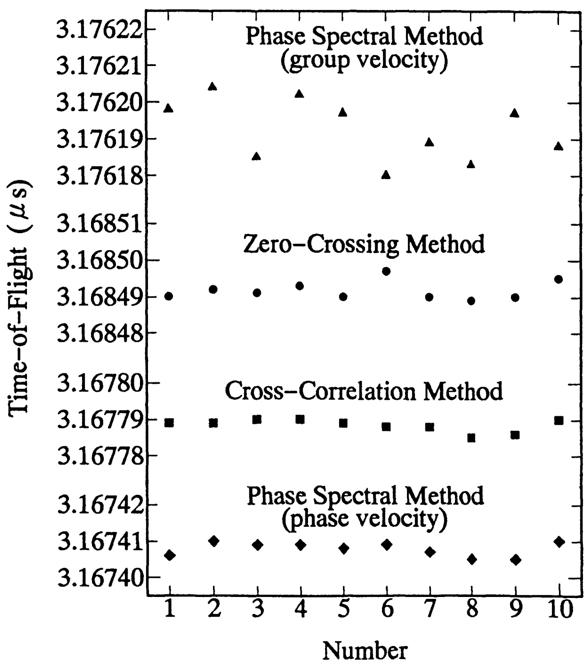


Figure 5. Variation of time-of-flight of longitudinal wave (2017-T3)

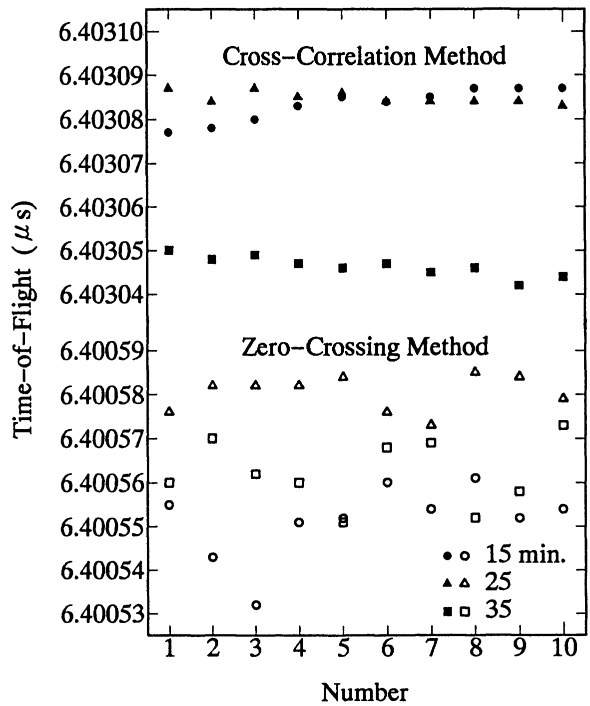


Figure 6. Variation of time-of-flight of transverse wave (2017-T3)

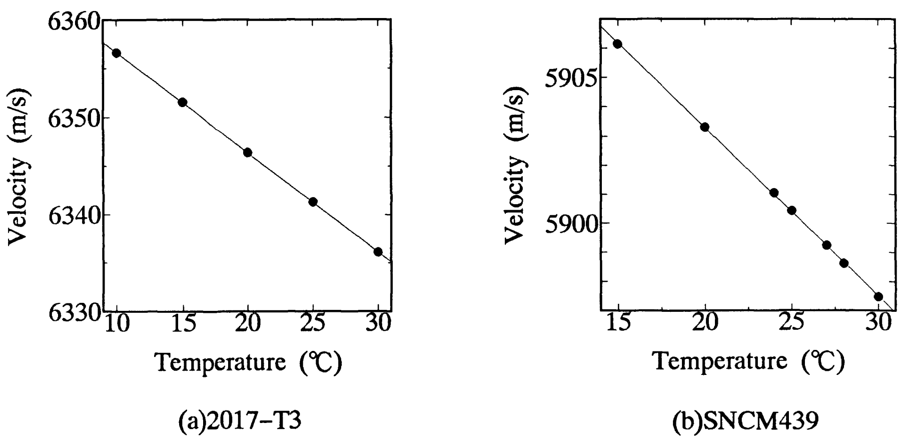
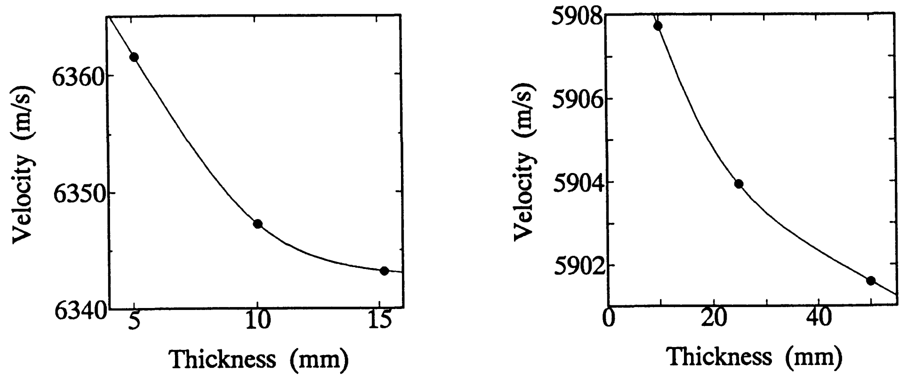


Figure 7. Temperature dependence of longitudinal velocity



(a)2017-T3 (b)SNCM439

Figure 8. Influence of specimen thickness

CONCLUSION

A high precision measurement system of the time-of-flight of ultrasonic pulse-echoes has been constructed with a conventional ultrasonic pulser/receiver, a transducer, a high-speed digital wave memory and a personal computer. To improve the precision of the measurement, it is essential that the pulsed excitation of a transducer synchronizes the sampling clock supplied to the A/D converter. Three digital signal processing procedure, the zero-crossing, cross-correlation and phase spectral methods, are implemented.

The measurement method was applied to the measurement of the longitudinal or transverse wave velocities of aluminum and steel alloy. The precision of the time-of-flight measurement, double of the standard deviation, is 4ps for longitudinal wave and 8ps for transverse wave on aluminum plate with the cross-correlation method. Thus, this system can be used for acoustoelastic stress measurement as well as a means of material evaluation with high resolution of velocity change.

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